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ABSTRACT

Research was conducted to determine the construct validity of event-related potential (ERP) amplitudes as indicators of individual differences in human cognitive characteristics. The differences were assessed using paper and pencil tests of cognitive styles, abilities, and aptitudes. Visual, auditory, and bimodal ERP's were recorded for each subject. Product moment and canonical correlation analyses, as well as principal factor analysis and varimax rotation, were conducted. There were significant relationships between some ERP's and cognitive characteristics. The more frequently appearing cognitive characteristics and ERP's contributing to the canonical correlations were the Armed Forces Qualification Test scores, the reading comprehension test scores, and the left and right frontal and parietal ERP's. Brain ERP's may be used for indexing certain cognitive styles, aptitudes, and abilities. They appear to reflect individual differences in intellectual function which indicate potential educational achievement or scholastic ability. The construct validity of brain ERP's as indicators of human cognitive processing was demonstrated by the results of the study. The study conclusions will assist the Navy in increasing the effectiveness of its training programs.
(Author/DWH)

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NPRDC TR 82-58

August 1982

VALIDATION OF BRAIN EVENT-RELATED POTENTIALS AS INDICATORS OF COGNITIVE STYLES, ABILITIES, AND APTITUDES

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Fifty Navy recruits were given 11 paper-and-pencil tests of cognitive styles, abilities, and aptitudes. Visual, auditory, and bimodal brain event-related potential (ERP) amplitudes were recorded from each of these subjects. Product-moment and canonical correlational analyses, as well as principal-factor analysis and varimax rotation, were conducted. All cognitive characteristics except reflection-impulsivity were significantly associated with at least some ERPs. The more frequently appearing

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cognitive characteristics and ERPs contributing to the canonical correlations were the Armed Forces Qualification Test scores, the reading comprehension test scores, and left and right frontal and parietal ERPs. Some ERPs and cognitive characteristics defined the same underlying dimensions, implying that they are related. The results demonstrated the construct validity of ERPs as indicators of individual differences in cognitive characteristics, especially crystallized intelligence.

FOREWORD

This research was performed under exploratory development work unit ZF63-522-010-03.06, Evaluating Evoked Potentials for Navy Training and Testing, under the sponsorship of the Chief of Naval Material (Office of Naval Technology). The goal of this work unit is to assess the feasibility of using brain event-related potentials (ERPs) in Navy training and testing.

This is the second in a series of reports prepared under this work unit. The first (NPRDC Tech. Rep. 82-8) discussed the use of ERP analysis to aid in the design of instructional procedures adapted to the information-processing strategies of individual students. It suggested the possibility of increasing Navy training efficiency by taking better advantage of the variabilities that exist among students in their sensory modalities. The purpose of this study was to ascertain the construct validity of brain ERPs as indicators of individual differences in cognitive processing.

Other NAVPERSRANDCEN publications that are related to this effort described student cognitive characteristics and academic achievement (NPRDC Tech. Reps. 79-1, 79-21, 79-30, and 80-23) and the relationship between ERP measures and performance (NPRDC Tech. Note 77-7 and Tech. Reps. 77-13, 79-13, and 80-26).

The results of this study are primarily intended for the Department of Defense training and testing research and development community.

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SUMMARY

Problem

Manpower shortages have made it necessary for the Navy to look for new procedures for increasing the effectiveness of its training programs. One way of doing this would be to develop techniques for adapting training to a wider range of student abilities, aptitudes, and cognitive styles. Advances in the computerized assessment of brain activity, especially in the measurement of brain event-related potentials (ERPs), suggest that this technology may be useful for estimating the cognitive characteristics of Navy trainees. If so, it may be possible to design instructional procedures that accommodate the differences among individual students. However, before brain-wave measures are employed in this manner, it must be established whether ERPs are valid indicators of individual differences in not only abilities and aptitudes but also cognitive styles.

Objective

The purpose of this research was to determine the construct validity of ERPs as indicators of individual differences in human cognitive characteristics, as those differences are assessed by traditional paper-and-pencil psychometric tests.

Approach

Paper-and-pencil tests of cognitive styles, aptitudes, and abilities were administered to 50 Navy recruits. Visual, auditory, and bimodal ERPs were recorded from each subject. Using the test scores and ERP measures as input, product-moment and canonical correlational analyses, as well as principal-factor analysis with varimax rotation, were conducted.

Results

All cognitive characteristics except reflection-impulsivity were significantly associated with at least some ERPs. The significant correlations between the cognitive attributes and ERPs ranged from .3 to .9 with many hovering around the high .3s. Noticeably higher correlations (in the .5s, .6s, and .7s) involve AFQT and reading comprehension with ERPs elicited bimodally in the left frontal, temporal, parietal, and occipital as well as right frontal and temporal brain regions. It seems that the more complex the cognitive characteristic (e.g., cognitive complexity, AFQT, reading comprehension versus verbal comprehension, field independence), the larger the number of ERPs that are related to that specific characteristic. The more frequently appearing variables contributing to the canonical correlations were AFQT, reading comprehension, and ERPs from electrode sites over the frontal and parietal areas. Some ERPs and cognitive characteristics (e.g., visual and bimodal asymmetry in the frontal brain sites and reading comprehension) define the same underlying independent dimensions. That is, they weight the same factors, implying that they are related.

Conclusions

1. There are significant relationships between some ERPs and cognitive characteristics (e.g., field independence was negatively correlated with visually evoked ERPs in the right occipital area).

2. It may be possible to use brain ERPs for indexing certain cognitive styles, aptitudes, and abilities.

3. ERPs appear to reflect individual differences in intellectual function, especially in crystallized intelligence, which reflects potential educational achievement or scholastic ability.

4. The results demonstrate the construct validity of brain ERPs as indicators of human cognitive processing.

Direction of Research

Since ERPs appear to be valid measures of individual differences in human information processing, especially in crystallized intelligence, they may provide a basis for adapting instructional techniques to Navy trainees and for developing improved methods of matching personnel to Navy jobs. Research is now underway that records ERPs prior to and during the initial learning and subsequent performance of Navy-relevant, real-world, information-processing tasks (e.g., tasks involving the detection, analysis, recognition, and classification of radar signals). Learning and performance indices are being related to the ERP measures to determine further their usefulness for designing adaptive instructional strategies and predicting student performance.

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INTRODUCTION

Problem

Manpower shortages have made it necessary for the Navy to look for alternative techniques for increasing the effectiveness of its training programs. One way of doing this would be to develop procedures for adapting training to a wider range of student abilities, aptitudes, and cognitive styles. Recent advances in the computerized assessment of brain activity, especially in the measurement of brain event-related potentials (ERPs), suggest that this technology may be useful for estimating the cognitive characteristics of Navy trainees. If so, then it may be possible to design instructional procedures that accommodate the differences among individual students. However, before brainwave measures are employed in this manner, it must be established whether ERPs are valid indicators of individual differences in not only abilities and aptitudes but also cognitive styles.

Objective

The purpose of this research was to determine the construct validity of brain ERPs as indicators of individual differences in cognitive characteristics, as those differences are assessed by traditional paper-and-pencil psychometric tests.

Background

The average ability level of Navy recruits has noticeably decreased since the all-volunteer force was implemented. Consequently, the Navy is seeking innovative training strategies that can be used to adapt instruction to a wider range of student abilities, aptitudes, and cognitive styles. In an effort to accommodate training to the individual differences between students, the Navy implemented computer-managed instruction (CMI). CMI is partially adaptive, since the students use self-study materials and learn at their own pace. A second strategy, the aptitude-treatment-interaction (ATI) approach, assumes that aptitudes, as measured by customary psychometric tests, interact with instructional strategies or treatments. Research has only partially supported the ATI notion (Cronbach & Snow, 1977; Federico, 1978, 1981). Improved techniques for accommodating instructional techniques to the cognitive attributes of individual students are still needed, however (Federico & Landis, 1979a, 1979b, 1980).

Another possible approach would be to assess individual differences in information processing styles, as indexed by ERPs, and then develop training strategies that exploit these differences. At least two different modes of information processing have been shown to be related to the brain's two hemispheres. A verbal, analytic, sequential, logical mode of information processing has been associated with left-hemisphere activity in most right-handed individuals. Conversely, a spatial, integrative, simultaneous, intuitive mode has been attributed to right-hemisphere activity. These two modes of processing were initially discovered by anatomical studies using subjects with war wounds, lesions, and "split-brains."

Computer technology and measures of brain electrical activity have been applied to the study of these processes. Electroencephalographic (EEG) and ERP records depict brain activity as minute signals recorded from the scalp. The EEG shows on-going activity while the ERP shows activity after stimulus events (e.g., light flashes or audible clicks). Typically, for people performing verbal tasks such as reading prose passages, there is decreased activity over the left hemisphere. For spatial tasks such as recognizing random shapes, there is generally a decrease in activity over the right hemisphere. Such

decreases may be considered indices of increased information processing within the affected hemisphere.

Some individuals employ a predominantly verbal-analytic cognitive style for learning, problem solving, and decision making, whereas others employ a predominantly spatial-integrative cognitive style (Bogen, 1969; Callaway, 1975; Dimond & Beaumont, 1974; Galin & Ellis, 1975; Galin & Ornstein, 1972; Kinsbourne, 1978; Knights & Bakker, 1976; Lewis, 1979, 1980; Lewis & Rimland, 1979, 1980; Ornstein, 1977).

Many studies have investigated relationships between brain ERPs and indices of intelligence. ERP latencies seem to vary inversely with measures of ability or intelligence (Bigum, Dustman, & Beck, 1970; Callaway, 1973, 1975; Chalke & Ertl, 1965; Ertl, 1969; Ertl & Schafer, 1969; Galbraith, Gliddon, & Busk, 1970; Gucker, 1973; Marcus, 1970; Shucard & Callaway, 1974; Shucard & Horn, 1972). Yet, some investigations failed to establish such a relationship (Barnet & Lodge, 1967; Engel & Fay, 1972; Henderson & Engel, 1974; Osborne, 1970; Rhodes, Dustman, & Beck, 1969).

Right hemisphere ERP amplitudes and asymmetry measures appear to be directly related to intelligence--although not always (Bigum, Dustman, & Beck, 1970; Galbraith, Gliddon, & Busk, 1970; Perry, McCoy, Cunningham, Falgout, & Street, 1976; Rhodes, Dustman, & Beck, 1969; Richlin, Weisinger, Weinstein, Giannini, & Morganstern, 1971; Shucard & Horn, 1973). Other ERP properties that have been explored with respect to intelligence have been habituation (Barnet, 1971), variability (Bigum, Dustman, & Beck, 1970; Callaway & Stone, 1969; Rhodes, Dustman, & Beck, 1969), and harmonic components (Bennett, 1968; Ertl, 1971, 1973; Shucard & Callaway, 1974, Weinberg, 1969).

A number of experiments have been conducted to explore associations between different aspects of human information processing and brain electrical activity (e.g., Buchsbaum & Silverman, 1970; Donchin, 1973; Donchin & Cohen, 1967; Donchin, Kubovy & Kutas, 1973; Friedman, Guyer-Christie, & Tumchuk, 1976; Horst, Johnson, & Donchin, 1980; Israel, Chesney, & Wickens, 1980; Israel, Wickens, Chesney, & Donchin, 1980; Pizzamiglio, 1976; Ray, Morell, Frediani, & Tucker, 1976; Shearer & Tucker, 1981; Squires, Petuchowski, Wickens, & Donchin, 1977; Tucker, 1981; Tucker & Shearer, 1977; Wickens, Mountford, & Schreiner, 1981). Very few of these investigations reported relationships between different ERPs and distinct cognitive styles as assessed by customary psychometric measures. Do ERPs have construct validity with respect to not only abilities and aptitudes but also cognitive styles?

Construct Validity

The American Psychological Association's Standards for Educational Tests and Manuals (1966, p. 13) states:

> Construct validity is evaluated by investigating what qualities a test measures; that is, by determining the degree to which certain explanatory concepts or constructs account for performance on the test. Essentially, studies of construct validity check on the theory underlying the test.

Investigations of construct validity are usually conducted to ascertain "what the test measures" in order to understand more fully the psychological characteristics or attributes contributing to test performance. When a test is proposed as a measure of a trait, its construct validity is established by determining its relationships to other tests

that purport to measure the trait. These relationships are often found by correlational or factor analytical methods.

APPROACH[1]

Generally, the approach consisted of correlating and factor analyzing ERPs with selected measures of individual differences in human information processing (i.e., cognitive styles, abilities, and aptitudes).

1. Cognitive styles (e.g., tolerance of ambiguity) are the dominant modes of information processing that people typically employ when perceiving, learning, or problem solving.

2. Abilities are intellectual capabilities (e.g., verbal comprehension) that are general and pervasive to the performance of many tasks.

3. Aptitudes are indices (e.g., mathematical or mechanical aptitude) used to select personnel to perform tasks that demand specific skills and to find the right person for a certain job or school.

Subjects

The subjects were right-handed, male, Caucasian recruits (N=50) from the Naval Training Center, San Diego, who were undergoing basic enlisted military instruction. Audition and vision of the subjects tested normal.

Cognitive Characteristics Measured

The cognitive characteristics measured in the study are reported in Table 1. The six cognitive style and three ability tests were administered to each subject counterbalanced with the ERP recordings. Scores for the two aptitude tests were obtained from Navy personnel records.

Instrumentation

Data were acquired on a field-portable computer system that included a Data General NOVA 2/10 central processing unit (CPU, 32K memory); a dual-drive floppy disk unit (Advanced Electronics Design, Inc., Model 2500); an optically isolated and multiplexing EEG unit with band pass set for 0.2-30 Hz; and a videographic display unit, integrated into the CPU, that presented visual stimuli to the subjects and displayed the analyzed ERP data. Permanent storage of all video information was obtained from a video hard copy unit (Tektronix Model 4632) (Lewis, 1979, 1980; Lewis & Rimland, 1979, 1980; Lewis, Rimland, & Callaway, 1977).

Stimuli

Visual (V) stimuli were computer-generated black and white checker-board patterns presented over the video monitor (Panasonic 14-inch Model WV 5400). Binocular visual field stimulation was about 9 degrees visual angle. Each check subtended about 17 minutes visual angle. Average background luminance was about 0.3 ftL and target luminance was about 5 ftL. The patterns were presented aperiodically, with interstimulus intervals averaging about 2 seconds (1.0-3.0 seconds).

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[1]The names of various equipments does not imply any endorsement of these equipments.

Table 1

Cognitive Characteristics Measured in this Research

Cognitive Characteristic	Description	Measurement Instrument
Field-independence vs. Field-dependence (FI.D)	Analytical vs. global orientation	Hidden Figures Test, Part I (Ekstrom, French, Harman & Dermen, 1976)
Conceptualizing Style (CONI)	Span of conceptual category	Clayton-Jackson Object Sorting Test (Clayton & Jackson, 1961)
Reflectiveness-Impulsiveness (REFL)	Deliberation vs. impulse	Impulsivity Subscale from Personality Research Test, Form E (Jackson, 1974)
Tolerance of Ambiguity (TOL)	Inclined to accept complex issues	Tolerance of Ambiguity Scale from Self-Other Test, Form C (Rydell & Rosen, 1966)
Category Width (CATW)	Consistency of cognitive range	Category Width Scale (Pettigrew, 1958)
Cognitive Complexity (COG)	Multidimensional perceptions of the environment	Group Version of Role Construct Repertory Test (Bieri, Atkins, Briar, Leaman, Miller, & Tripodi, 1966)
Verbal Comprehension (VERB)	Understanding the English language	Vocabulary Test II (Ekstrom et al., 1976)
Visualization (SPA)	Manipulating spatial patterns	Surface Development Test (Ekstrom et al., 1976)
Logical Reasoning (LOG)	Deducing from premise to conclusion	Nonsense Syllogisms Test, Part I (Ekstrom et al., 1976)
General Aptitude (AFQT)	Comprehending language, solving arithmetic problems, and visualizing objects in space	Word Knowledge Subtest, Arithmetic Reasoning Subtest, and Space Perception Subtest, Armed Services Vocational Aptitude Battery
Reading Comprehension (RGL)	Understanding English words and prose passages	Gates-MacGinitie Reading Test, Level D, Form 1 (Gates & MacGinitie, 1965)

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Auditory (A) clicks were presented binaurally over headphones (Sennheiser Model 424X) aperiodically about every 2 seconds (1.0-3.0 second interstimulus intervals). Click intensity was aout 65 dB (A) (Bruel and Kjaer Impulse Sound Level Meter, Model 2209, One-Third Octave Filter Set, Model 1616). Headphone leads were shielded to minimize click artifacts.

Biomodal (B) presentation included simultaneous presentation of the visual and auditory stimuli. These stimuli were presented aperiodically about every 2 seconds (1.0-3.0 seconds).

During all recording periods, white noise was used for masking. It was presented to the subjects through the headphones and via a speaker in the sound chamber at a level of approximately 50 db (A).

Procedure

Recording Sites

Eight channels of visual, auditory, and bimodal ERP data were acquired from four pairs of homologous sites, as shown in Figure 1. Sites F3 and F4 are over the frontal brain region, an association area; sites T3 and T4 are over the temporal region, a primary auditory reception area where many visual and auditory nerves interconnect; sites P3 and P4 are over the parietal region, a primary association area; and sites O1 and O2 are over the occipital region, a primary visual reception area (Jasper, 1958). Ground was at Pz in the mid-parietal area. Sites designated by odd numbers denote left hemisphere locations; and those designated by even numbers, right hemisphere locations.

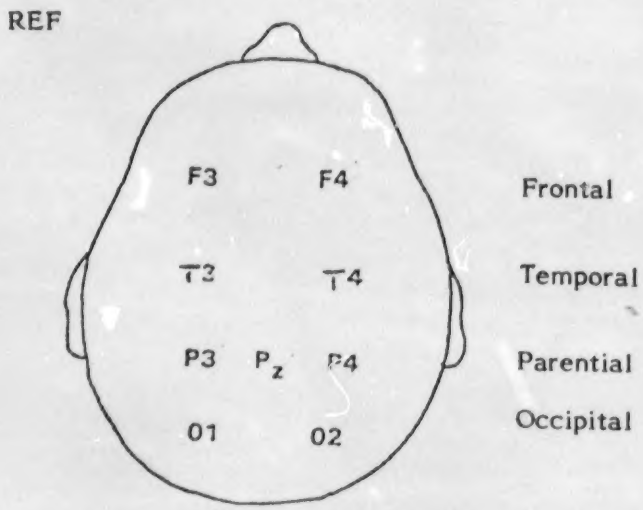

Figure 1. Electrode site montage.

Electrodes

The subjects were prepared for recording after they had received brief instruction. They completed a brief background questionnaire and signed a privacy act and volunteer consent form. An elastic helmet (Lycra) fitted with plastic holders for the electrodes was

placed on the subject's head. Each subject's hair was parted and scalp cleaned with an alcohol-impregnated cotton swab that was placed through the holders. Electrode cream was placed down the holders and rubbed into the scalp. The electrodes were Beckman miniatures (11 mm) with a clear plastic extension tube (38 mm long) attached and filled with electrolytic solution. A small sponge (microcell foam) soaked with electrolyte held the solution in the tube and made contact with the electrode paste on the scalp. The extension tube not only held the electrode in place but also minimized the slow potential drift due to scalp temperature change that would have otherwise been picked up at the recording site. A Beckman mini-electrode fitted with a standard two-sided adhesive wafer served as a reference electrode on the nose.

The helmet and all 10 electrodes could be attached in 6-8 minutes with impedance readings of 2-3K ohms. After all electrodes were in place, the subjects were instructed to observe their real-time EEG activity on the oscilloscope display. They were then instructed to move their jaws, eyebrows, etc. so that they could observe how muscle artifacts could contaminate the ERP data. The subject was then seated in a sound chamber in alignment with the video monitor. A hand-held switch allowed the subject to suspend all stimulus presentation and analysis operations to eliminate artifact. Additional artifact rejection was available by the console operator prior to storing the data.

ERP Data

The visual and auditory ERP data were retrieved from a floppy diskette and the required computations were performed. The data were then displayed on the video monitor and hard copies were obtained. Bimodal ERP data were also computed and displayed in a similar manner.

Eight channels of visual and auditory ERP data are overlaid in Figure 2. Root mean square (RMS) and standard deviation (SD) amplitude values are presented, along with the waveform mean values for the half-second post-stimulus epoch (533 msec). SD amplitude values (in microvolts (μV)) are normalized (waveform mean set to zero) RMS values (in μV). For all analyses, only SD amplitude values (in μV) were used. Prestimulus waveforms (133 msec) were also recorded and displayed for each channel. Calibration, polarity, DC offset, time base, and other descriptive information were also displayed. The waveforms in the left column were derived from the left hemisphere (LH). The waveforms from top to bottom were from the front to the back of the head at frontal, temporal, parietal, and occipital sites (F3, T3, P3, O1). Right hemisphere (RH) ERP data from sites F4, T4, P4, and O2 were represented in the right column.

In addition to the directly recorded ERP amplitudes, two indices were derived to reflect different hypothesized properties of brain behavior. First, in order to assess the relative functioning between the hemispheres, ERP asymmetry measures were examined between homologous electrode sites. An asymmetry index was defined as the right minus left hemisphere amplitude (RH-LH) for a specific brain area. If this expression is positive (negative), then there is a decrease in activity at the left (right) hemisphere site, which indicates increased information processing within that particular location. Second, in order to appraise sensory interaction and its effects on information processing, the relationship between independent single modality presentations (visual or auditory) and the joint bimodal presentation (simultaneous stimulation of visual checkerboard patterns and auditory clicks) was determined. A sensory interaction index was defined as BERP-(VERP + AERP) (Lewis & Froning, 1981; Lewis, Federico, Froning & Calder, 1981). If the result of this expression is positive, then bimodal stimulation produces a greater magnitude response than the sum of separate visual or auditory stimulation. This indicates excitatory or facilitory activity in the brain's nervous system. If the expression

is negative, then attenuated activity occurs in the nervous system when auditory stimulation is presented at the same time as visual stimulation.

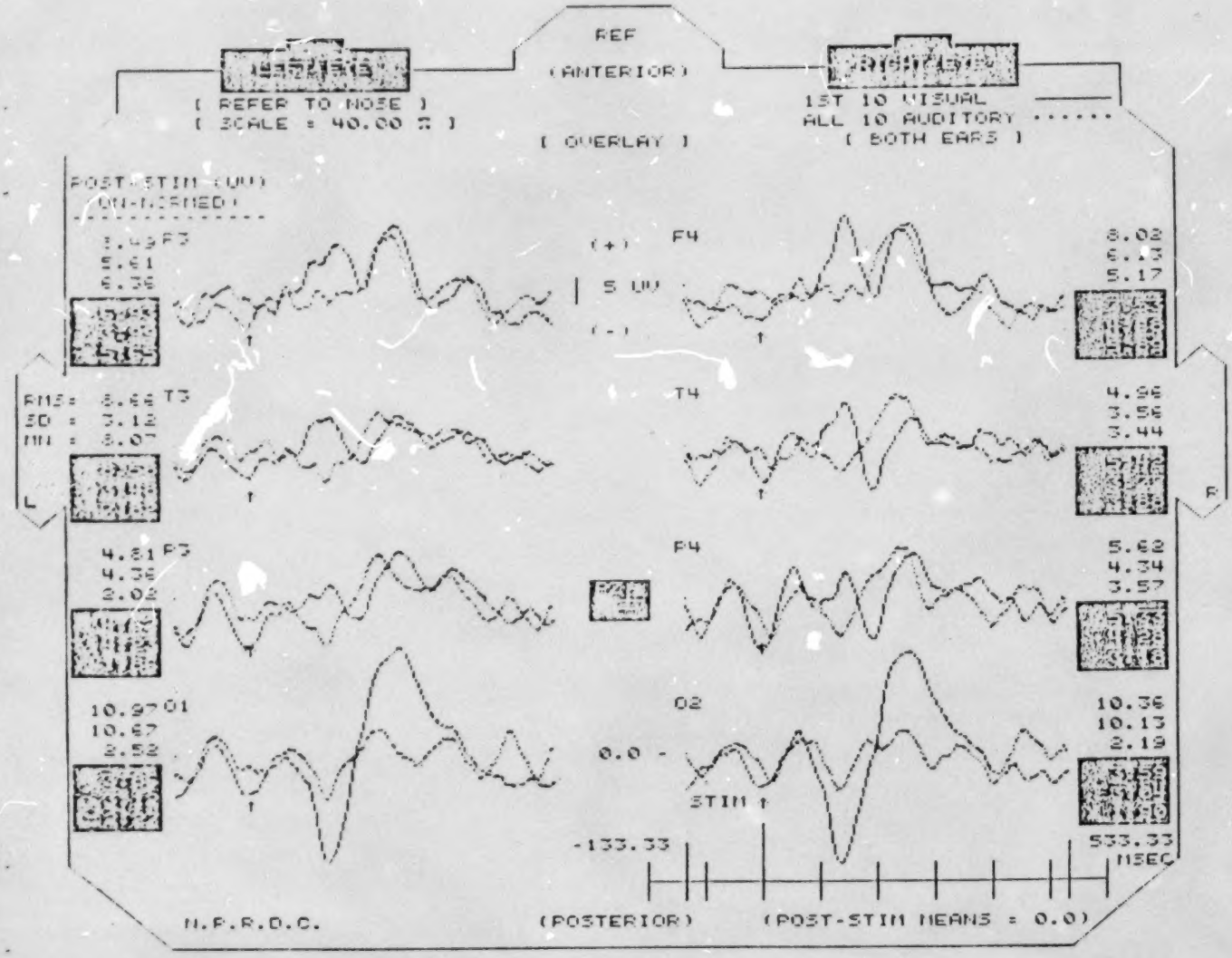

Figure 2. Sample VERP and AERP data. The left column of data is from the left hemisphere; and the right column, from the right hemisphere. From top to bottom, the records are from the frontal, temporal, parietal, and occipital regions.

Statistical Analyses

The relationships between visual, auditory, and bimodal ERPs, as well as those between asymmetry measures, sensory interaction indices, and cognitive characteristics, were examined by conducting product-moment and canonical correlational analyses. Canonical analysis (Cooley & Lohnes, 1962) derives a linear combination for each set of cognitive characteristics and ERPs such that it maximizes the correlation between them. Instead of computing the correlation between two univariate variables, it computes the correlation between two linear combinations--principal components--of multivariate variables. The absolute values of the weights of the variables indicate their relative contributions or importance to the respective linear combinations or canonical variates. A principal-factor analysis without iteration was also computed for the cognitive characteristics together with only the asymmetry ERPs to determine the independent dimensions that account for a considerable amount of the underlying variability of these indices. This initial factor solution was rotated according to the varimax procedure to achieve a simpler structure and a more meaningful pattern. Rules of thumb for achieving the simplest factor structure and more theoretically meaningful factors have been summarized by Harman (1967, p. 98).

RESULTS

Product-moment Correlational Analyses

The descriptive data for cognitive characteristics, ERPs, ERP asymmetries, and sensory interactions are presented in Tables 2, 3, and 4 respectively. As can be seen in Table 3, mean bimodal ERPs (BERPS) were larger than mean visual ERPs (VERPs) or auditory ERPs (AERPs) at the same electrode sites. Mean visual ERPs were larger than auditory ERPs, especially in right hemisphere sites.

The intercorrelation matrices presented in Tables 5, 6, and 7 show that all cognitive characteristics except REFL were significantly ($p < .05$) associated with at least some ERPs. The significant correlations ranged from .3 to .9, with many of them hovering around the high .3s. Noticeably higher correlations (in the .5s, .6s, and .7s) involve AFQT and RGL with ERPs elicited bimodally in the left parietal and occipital as well as in both frontal and temporal areas. Some of the correlations imply that the more complex the cognitive characteristic (e.g., COG, AFQT, RGL versus VERB, FLD), the larger the number of ERPs related to that characteristic.

1. Correlations Between ERPs and Measures of Cognitive Style. Patterns of correlations in Table 5 indicate that the electrical activity in the parietal and occipital regions of the brain is associated with measures of cognitive styles (i.e., with TOL, CATW, and COG). Some of the significant correlations between cognitive characteristics and ERPs included:

a. FLD was negatively correlated with visual ERPs in the right occipital region.

b. CON was negatively correlated with visual ERPs in both occipital areas.

c. TOL was positively correlated with bimodal ERPs at the left parietal and occipital and the right temporal regions.

d. COG was negatively correlated with visual ERPs in the right temporal and in both parietal and occipital areas.

Table 2

Descriptive Data for Cognitive Characteristics

Characteristic	$\bar{X}$	SD
Cognitive Style		
FLD	4.40	3.28
CON	11.70	4.18
REFL	5.44	3.84
TOL	5.82	2.26
CATW	30.00	11.13
COG	73.66	21.98
Aptitudes and Abilities		
AFQT	63.50	18.67
RGL	10.59	1.96
VERB	6.74	2.51
SPA	28.34	16.76
LOG	.48	4.02

Note. N equals 50.

Table 3

Descriptive Data for ERPs and ERP Asymmetries

ERP Index / Hemisphere / Electrode Site	Visual ERPs		Auditory ERPs		Bimodal ERPs	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
ERPs						
Left Hemisphere						
Frontal	2.76	1.17	2.64	1.04	4.44	2.04
Temporal	2.23	.84	2.44	.82	3.07	1.43
Parietal	2.82	1.24	2.97	1.02	4.04	1.60
Occipital	3.87	1.47	3.00	.91	4.85	1.54
Right Hemisphere						
Frontal	2.81	1.31	2.68	1.01	4.29	2.02
Temporal	2.60	.95	2.40	.73	3.43	1.46
Parietal	3.07	1.24	2.82	1.04	4.08	1.56
Occipital	3.65	1.16	2.76	.81	4.86	1.60
Asymmetries						
Right Minus Left Hemisphere						
Frontal	.05	.67	.04	.55	-.15	.76
Temporal	.36	.80	-.04	.85	.36	.96
Parietal	.25	.75	-.15	.75	.04	.91
Occipital	-.21	.88	-.24	.64	.01	.96

Note. N equals 50. $\bar{X}$ values are in standard deviation microvolts.

Table 4

Descriptive Data for Sensory Interactions

ERP Index Left Electrode Site	Right Hemisphere		Hemisphere	
	$\bar{X}$	SD	$\bar{X}$	SD
Sum				
Frontal	5.40	1.96	5.49	1.91
Temporal	4.68	1.41	5.00	1.45
Parietal	5.79	1.99	5.88	2.00
Occipital	6.86	1.98	6.15	2.43
Interaction				
Frontal	-0.96	2.01	-1.21	2.01
Temporal	-1.61	1.46	-1.57	1.25
Parietal	-1.75	1.54	-1.81	1.42
Occipital	-2.01	1.71	-1.55	1.50

Note. N equals 50. $\bar{X}$ values are in standard deviation microvolts. Sum equals VERPs plus AERPs. Interaction equals [BERP - (VERP + AERP)].

Table 5

Correlations Between ERPs and Measures of Cognitive Style

ERP Mode / Hemisphere / Electrode Site	Cognitive Style Measures					
	FLD	CON	REFL	TOL	CATW	COG
Visual ERPs						
Left Hemisphere						
Frontal	-.20	-.13	.06	-.07	-.25	-.24
Temporal	-.17	-.31*	.07	.02	-.12	-.26
Parietal	-.22	-.21	.07	-.13	-.09	-.45**
Occipital	-.27	-.30*	-.10	.05	-.17	-.43**
Right Hemisphere						
Frontal	-.08	-.14	.13	-.04	-.24	-.26
Temporal	-.16	-.18	.06	.05	-.21	-.30*
Parietal	-.20	-.23	-.04	-.06	-.10	-.36**
Occipital	-.39**	-.30*	-.12	.06	-.08	-.32*
Auditory ERPs						
Left Hemisphere						
Frontal	-.18	.05	-.10	-.12	-.18	-.23
Temporal	-.09	.03	.04	-.06	-.11	-.24
Parietal	-.05	.06	.05	-.04	-.02	-.24
Occipital	-.03	-.19	-.03	.09	-.07	-.33*
Right Hemisphere						
Frontal	-.16	.12	-.08	-.10	-.09	-.15
Temporal	-.08	.04	-.09	.14	-.31*	-.18
Parietal	.00	.06	-.06	-.03	-.10	-.25
Occipital	.00	-.12	-.15	-.01	-.09	-.18
Bimodal ERPs						
Left Hemisphere						
Frontal	-.04	.01	.10	.09	-.10	-.16
Temporal	.01	-.22	-.20	.24	-.13	-.19
Parietal	-.03	-.15	.12	.29*	-.28*	.10
Occipital	-.07	-.18	.06	.35*	-.19	.03
Right Hemisphere						
Frontal	-.01	-.09	-.06	.20	-.05	-.19
Temporal	-.06	-.21	-.24	.31*	.00	-.09
Parietal	.19	-.05	.14	.04	-.03	-.08
Occipital	.00	.11	.00	.03	-.12	-.08

*$r(48) \geq .28$; $p < .05$.
**$r(48) \geq .36$; $p < .01$.

Table 6

Correlations Between ERPs and Measures of Aptitude and Ability

ERP Mode / Hemisphere / Electrode Site	Aptitude and Ability Measures				
	AFQT	RGL	VERB	SPA	LOG
Visual ERPs					
Left Hemisphere					
Frontal	.52**	.33*	-.15	-.26	-.10
Temporal	.31*	.40**	-.14	-.18	-.21
Parietal	.31*	.30*	-.10	-.27	-.17
Occipital	.25	.23	-.08	-.27	-.16
Right Hemisphere					
Frontal	.46**	.32	-.11	-.15	-.27
Temporal	.27	.37**	-.16	-.18	-.43**
Parietal	.32*	.28*	-.12	-.23	-.22
Occipital	.22	.07	-.16	-.21	-.18
Auditory ERPs					
Left Hemisphere					
Frontal	.35*	.24	-.35*	-.23	-.08
Temporal	.38**	.39**	-.15	-.23	-.11
Parietal	.35*	.33*	.02	-.11	-.14
Occipital	.16	.13	.10	-.22	-.10
Right Hemisphere					
Frontal	.19	.02	-.36**	-.22	.02
Temporal	.25	.26	-.26	-.36**	-.20
Parietal	.24	.27	.03	-.24	-.30*
Occipital	.28*	.24	.10	-.06	-.17
Bimodal ERPs					
Left Hemisphere					
Frontal	.58**	.77**	.00	-.13	-.10
Temporal	.40**	.59**	-.17	-.23	-.08
Parietal	.93**	.78**	-.06	-.04	-.06
Occipital	.69**	.78**	-.08	-.07	-.16
Right Hemisphere					
Frontal	.46**	.63**	-.08	-.25	-.13
Temporal	.36**	.47**	-.14	-.09	.00
Parietal	.00	.06	.06	.16	-.34*
Occipital	.00	.01	-.05	-.02	-.29*

*$r(48) \geq .28$; $p < .05$.
**$r(48) \geq .36$; $p < .01$.

Table 7

Correlations Between ERP Asymmetries and Measures of Cognitive Style

ERP Mode / Electrode Site	Cognitive Style Measures					
	FLD	CON	REF	TOL	CATW	COG
Visual ERPs						
Frontal	.03	-.03	-.05	.11	-.02	.15
Temporal	-.06	.11	.00	.00	.19	.28*
Parietal	.06	.11	.04	.03	.17	.16
Occipital	.02	.00	-.10	.06	-.15	.08
Auditory ERPs						
Frontal	.07	.00	-.15	.00	-.11	-.01
Temporal	.04	.11	-.14	-.14	.00	.24
Parietal	.02	-.13	-.06	.31*	-.23	-.18
Occipital	-.17	.00	-.08	.13	.07	.01
Bimodal ERPs						
Frontal	.05	-.19	-.27	.18	.10	-.06
Temporal	-.12	.00	-.07	.14	.21	.17
Parietal	-.22	-.05	-.01	-.10	-.25	-.27
Occipital	-.16	-.17	.07	.04	-.14	-.30*

*$r(48) \geq .28$; $p < .05$.

2. Correlations Between ERPs and Measures of Aptitude and Ability. Generally, the patterns of correlations in Table 6 reveal that visual ERPs in the frontal, temporal, and parietal areas are positively related to AFQT and RGL scores. However, only the left frontal, temporal, and parietal regions seem to be associated with AFQT and RGL when auditory stimuli are used to elicit ERPs. Also, bimodal ERPs indicate that the left frontal, temporal, parietal, and occipital areas are strongly positively associated with AFQT and RGL but only the right frontal and temporal areas are related to AFQT and RGL. That is, it appears that only the right forward part of the brain, the frontal and temporal regions, are associated with AFQT and RGL when employing bimodal stimuli. There does not seem to be any contribution to AFQT and RGL from the right parietal and occipital areas when using bimodal stimuli to evoke ERPs. Some of the significant correlations given in Table 6 included:

a. VERB was negatively correlated with auditory ERPs in both frontal areas.

b. SPA was negatively correlated with auditory ERPs at the right temporal region.

c. LOG is negatively correlated with visual ERPs at the right temporal site and with auditory and bimodal ERPs at the right parietal site.

d. AFQT was positively correlated with visual ERPs in the left temporal region and both frontal and parietal regions. It was also correlated with bimodal ERPs in the left parietal and occipital areas and in both frontal and temporal areas.

e. RGL was positively correlated with bimodal ERPs in the left parietal and occipital sites and in both frontal and temporal sites.

3. Correlations Between ERP Asymmetries and Measures of Cognitive Style. Table 7 reveals that there were few significant correlations between ERP asymmetries and measures of cognitive style. There are only three significant relationships in Table 7, and these do not produce any discernible pattern. For example, TOL was positively correlated with auditorily elicited asymmetry at the parietal areas.

4. Correlations Between ERP Asymmetries and Measures of Aptitude and Ability. Patterns of correlations in Table 8 reveal that bimodal ERP asymmetries in the back part of the brain (i.e., the parietal and occipital areas) are positively associated with AFQT and RGL, but the forward part (i.e., the frontal and temporal regions) does not appear to be significantly related to them. Also, visual ERP asymmetries in the parietal and temporal areas seem to be negatively associated with RGL, and visual ERP asymmetry in the parietal region seems to be negatively associated with AFQT. RGL was positively correlated with bimodal asymmetry in the parietal and occipital areas.

5. Correlations Between Sensory Interactions and Measures of Cognitive Style. Table 9 reveals that generally the sums of visual and auditory ERPs are significantly negatively related to COG for the left frontal, temporal, and occipital areas and the right frontal area, but are positively related to the right parietal and occipital areas. More importantly, COG appears to be positively associated with indices of sensory interaction for the left and right hemisphere sites. It is interesting to note that TOL is positively related to the left parietal and occipital as well as the right frontal and temporal regions. CATW was positively related to sensory interaction at the right parietal and occipital areas.

6. Correlations Between Sensory Interactions and Measures of Aptitude and Ability. The pattern of the strongest significant correlations in Table 10 suggests that AFQT and RGL are positively associated with (a) the sum of visual and auditory ERPs elicited in the right parietal and occipital regions, and (b) the sensory interaction indices in the left parietal and occipital regions. It should be noted that there are hardly any significant correlations between right hemisphere sensory interaction indices and AFQT and RGL. RGL was positively correlated with the sensory interaction indices for the left parietal and occipital as well as for both frontal areas; SPA was positively related to the index of sensory interaction for the right parietal and occipital areas.

Table 8

Correlations Between ERP Asymmetries and Measures of Aptitude and Ability

ERP Mode / Electrode Site	Aptitude and Ability Measures				
	AFQT	RGL	VERB	SPA	LOG
Visual ERPs					
Frontal	.00	-.04	-.03	.06	-.08
Temporal	-.12	-.29*	-.09	.18	.02
Parietal	-.32*	-.40**	.00	.03	.20
Occipital	-.15	-.15	-.08	-.09	-.06
Auditory ERPs					
Frontal	-.14	-.08	.00	-.19	-.22
Temporal	.11	.11	-.02	.23	-.07
Parietal	-.21	-.07	-.09	-.26	-.26
Occipital	-.14	-.30*	-.04	-.04	-.18
Bimodal ERPs					
Frontal	-.24	-.27	-.14	-.20	-.04
Temporal	.00	-.15	-.03	.22	.13
Parietal	.50**	.32*	-.28*	-.28*	-.10
Occipital	.40**	.47**	-.17	-.24	-.19

*$r(48) \geq .28$; $p < .05$.
**$r(48) \geq .36$; $p < .01$.

Table 9

Correlations Between Sensory Interactions and Measures of Cognitive Style

ERP Mode / Hemisphere / Electrode Site	Cognitive Style Measures					
	FLD	CON	REFL	TOL	CATW	COG
Sum						
Left Hemisphere						
Frontal	-.16	-.10	.07	-.10	-.07	-.40**
Temporal	-.21	-.31*	-.09	-.07	-.16	-.47**
Parietal	-.14	-.03	.05	-.08	-.21	-.25
Occipital	-.14	-.10	.00	.10	-.29*	-.29*
Right Hemisphere						
Frontal	-.12	-.11	.00	-.06	-.12	-.35*
Temporal	-.34*	-.38**	-.06	.11	.05	-.19
Parietal	.17	-.05	.17	.28*	.04	.43**
Occipital	.19	-.01	.08	.21	-.10	.31*
Interaction						
Left Hemisphere						
Frontal	.16	.14	.01	.22	-.02	.36**
Temporal	.26	.17	-.08	.13	.07	.37**
Parietal	.10	-.12	.08	.37**	-.08	.35*
Occipital	.08	-.09	.07	.30*	.12	.37**
Right Hemisphere						
Frontal	.16	.05	-.05	.30*	.11	.28*
Temporal	.24	.07	-.08	.30*	.10	.26
Parietal	.17	.19	-.07	.08	.37**	.39**
Occipital	.08	-.04	.18	.22	.30*	.33*

Note. Sum equals VERPs plus AERPs. Interaction equals [BERP - (VERP + AERP)].

*$r(48) \geq .28$; $p < .05$.
**$r(48) \geq .36$; $p < .05$.

Table 10

Correlations Between Sensory Interactions and Measures of Aptitude and Ability

ERP Mode Hemisphere Electrode Site	Aptitude and Ability Measures				
	AFQT	RGL	VERB	SPA	LOG
Sum					
Left Hemisphere					
Frontal	.38**	.36**	-.05	-.23	-.18
Temporal	.26	.23	.00	-.30*	-.16
Parietal	.42**	.23	-.26	-.22	-.17
Occipital	.30*	.37**	-.24	-.30*	-.38**
Right Hemisphere					
Frontal	.32*	.31*	-.06	-.27	-.29*
Temporal	.22	.10	-.06	-.13	-.09
Parietal	.53**	.50**	.24	.33*	.13
Occipital	.39**	.52**	.11	.18	.14
Interaction					
Left Hemisphere					
Frontal	.11	.33*	.06	.13	.12
Temporal	.05	.25	-.14	.14	.11
Parietal	.54**	.56**	.19	.17	.09
Occipital	.46**	.48**	.18	.26	.25
Right Hemisphere					
Frontal	.04	.25	-.01	.10	.26
Temporal	.09	.32*	-.08	.09	.23
Parietal	.18	.16	-.01	.32*	-.15
Occipital	.13	.20	-.18	.36**	.27

*$r(48) \geq .28$; $p < .05$.
**$r(48) \geq .36$; $p < .01$.

Canonical Correlational Analyses

Table 11 summarizes and highlights the significant canonical analyses between all the cognitive characteristics and some ERPs. The significant canonical correlations reveal that some cognitive attributes and ERPs have from 48 to 95 percent variance in common. The more frequently-appearing cognitive characteristics that contribute to the canonical correlations are the complex attributes AFQT and RGL, as well as ERPs over the frontal and parietal areas. More specifically, Table 11 represents the nature of the significant relationships between all the cognitive attributes and the different ERPS. The variables that contribute to these linear combinations (canonical variates), as well as all other canonical functions, are listed in the order of their importance according to the relative size of the absolute values of their canonical weights. For example, spotlighting only some of the various significant canonical correlations between the cognitive characteristics and ERPs, Table 11 discloses, in addition to many others, the following relationships:

1. Visual ERPs from both hemispheres indicate that AFQT, RGL, and SPA are associated with ERPs over the left frontal and temporal and over both occipital areas.

2. Bimodal ERPs from both hemispheres indicate that AFQT and RGL are correlated with activity in the left parietal and frontal sites.

3. Bimodal ERPs from the left hemisphere indicate that AFQT is associated with left parietal activity; RGL, AFQT, and CATW are related to left frontal activity.

4. Visual, auditory, and bimodal asymmetries indicate that RGL, SPA, TOL, and CATW are related to visual and bimodal asymmetry in the occipital regions as well as auditory asymmetry in the frontal and temporal regions.

5. Visual plus auditory ERPs for both hemispheres indicate that AFQT is related to activity in the left frontal and both parietal sites.

6. Sensory interaction for the left hemisphere indicates that AFQT, TOL, CON, and VERB are related to the left frontal, parietal, and occipital areas.

Factor Analysis

There were 52 ERP measures and 11 cognitive characteristics, but only 50 subjects upon which to base a principal-factor solution with Varimax rotation. Consequently, if all ERP measures had been used as input data, then the derived factors would have been very unstable and indeterminant because of the large number of variables relative to the small number of subjects. The results of such analyses would have been only suggestive at the very best. Also, this situation would have violated accepted criteria for selecting the number of subjects for factor analysis. Some researchers (e.g., Cattell, 1966) suggest that the proper ratio of subjects to variables is from 2:1 to as high as 5:1. With small ratios, common factor variance would be inflated, resulting in the extraction of more factors than necessary, and at the same time upsetting simple structure rotation and factor recognition (Guertin & Bailey, 1970). Under these circumstances, factor analyses would have been questionable, if not meaningless. Therefore, instead of using all 52 ERP measures, only the 12 asymmetry indices were used as inputs to the factor analysis. When these were added to the 11 cognitive characteristics, the ratio of subjects to variables was 50:23--slightly better than the 2:1 lower bound mentioned in Cattell's guidelines.

Table 11

Summary of Significant Canonical Analysis Between Cognitive Characteristics and Event-related Potentials

Canonical Analysis No.	Number of Significant Canonical Variate Pairs	ERP Measures	Significance of Canonical Correlation						Abbreviated Canonical Variate Pairs[a]	
			R_c	R_c^2	λ	χ^2	d.f.	p	Cognitive Characteristics	Event-related Potentials[b]
1	1	VERPs (BH)	.79	.62	.04	122.42	88	.009	-.44SPA + 1.54AFQT - 1.15RGL	1.01VLF - .61VLT - .57VLO + .79VRO
2	1	VERPs (LH)	.74	.55	.16	73.88	44	.003	-.49SPA + 1.41AFQT - .82RGL	1.19VLF - .84VLT
3	1	VERPs (RH)	.72	.52	.18	70.89	44	.006	73COG - 1.11AFQT + .59RGL	-.42VRF - .69VRO
4	1	AERPs (RH)	.69	.48	.20	66.54	44	.016	-.84VERB + .59LOG + .49AFQT -.60RGL	.79ARF + .72ART - 1.52ARP
5	3	BERPs (BH)	.97	.95	.00	226.02	88	.000	-.68AFQT - .35RGL	-.42BLF - .74BLP
			.78	.60	.06	108.88	70	.002	-.81SPA + 1.17AFQT - 1.25RGL	-1.27BLF + 1.21BLP -1.24BLO + 1.08BRF
			.75	.56	.15	73.02	54	.043	-.40TOL + .69CATW - 1.23SPA -.54AFQT + .90RGL	.53BLT - .66BLO + 1.10BRF
6	2	BERPs (LH)	.96	.92	.02	153.75	44	.000	-.77AFQT	-.81BLP
			.78	.54	.28	51.88	30	.008	-.54CATW + 1.11AFQT - 1.5RGL	-.88BLF
7	1	BERPs (RH)	.79	.62	.17	72.88	44	.004	-.66CATW + .84SPA - .91RGL	-.90BRF

[a]Only those cognitive characteristics and ERPs having canonical weights or loadings whose absolute values are equal to or greater than .40 are tabled.

[b]Legend

A = auditory ERPs
B = bimodal ERPs
F = frontal lobe
LH = left hemisphere
O = occipital lobe
P = parietal lobe
RH = right hemisphere
RL = right minus left hemisphere amplitude
T = temporal lobe
V = visual ERPs
VA = visual + auditory ERPS
BH = both hemispheres

Table 11 (Continued)

Canonical Analysis No.	Number of Significant Canonical Variate Pairs	ERP Measures	Significance of Canonical Correlation						Abbreviated Canonical Variate Pairs[a]	
			R_c	R_c^2	λ	χ^2	d.f.	p	Cognitive Characteristics	Event Related-potentials[b]
8	1	V, A, & B asymmetry	.84	.70	.01	167.85	132	.019	.46TOL + .40CATW - .52SPA - .67RGL	-1.06VRLO + .59ARLF - .47ARLT - .55BRLO
9	1	Bimodal asymmetry	.75	.58	.17	72.05	44	.005	1.11AFQT	1.08BRLP
10	3	Sum[c] (BH)	.94	.88	.01	193.19	88	.000	-.87AFQT	-.40VALF - .66VALP - .82VALP
			.79	.62	.06	111.95	70	.001	-1.31AFQT + 1.60RGL	1.20VALF - .96VALP + .64VALO - .55VALF - .49VALT - .80VALP + 1.07VARO
			.71	.51	.15	74.05	54	.036	.48FLD - .55CATW + .76COG	-.58VALF - .46VALT + .74VALP
11	1	Sum (LH)	.72	.51	.19	67.21	44	.014	.86COG - .89AFQT	-.42VALF - .45VALT
12	2	Sum (RH)	.82	.68	.10	96.47	44	.000	.44AFQT + .47RGL	.61VALF + .79VALP
			.72	.51	.30	49.92	30	.013	-.52FLD + .67CATW - .54COG -.40LOG + .82AFQT - .54RGL	.78VART
13	2	Interaction[d] (BH)	.88	.77	.01	168.84	88	.000	-.55VERB - .92AFQT	-.93BSP - .56BSO + .89BSF
			.82	.68	.06	110.83	70	.001	.66CATW - .59VERB + .62RGL	.40BSF + .62BSO
14	1	Interaction (LH)	.81	.66	.12	86.28	44	.000	.42CON - .43TOL - .40VERB - .92AFQT	.79BSF - .95BSP - .50BSO
15	1	Interaction (RH)	.81	.65	.13	83.33	44	.013	.56CATW + .48COG - .42VERB - .42AFQT + .80RGL	.47BSP + .48BSO

[a]Only those cognitive characteristics and ERPs having canonical weights or loadings whose absolute values are equal to or greater than .40 are tabled.

[b]Legend

A = auditory ERPs
B = bimodal ERPs
F = frontal lobe
LH = left hemisphere
O = occipital lobe
P = parietal lobe
RH = right hemisphere
RL = right minus left hemisphere amplitude
T = temporal lobe
V = visual ERPs
VA = visual + auditory ERPS
BH = both hemispheres

[c]Sum equals VERPs plus AERPs.
[d]Sensory interaction equals [BERP -(VERP + AERP)].

Visual, auditory, and bimodal asymmetry measures were factor analyzed together with the cognitive characteristics indices because lateral hemispheric differences may be related to dominant modes of information processing that individuals typically employ when perceiving, learning, or problem solving. By factor analyzing brain asymmetry measures together with some cognitive styles, abilities, and aptitudes, the independent dimensions that account for much of the underlying variability of these indices can be identified. This would be useful for establishing the construct validity of brain ERPs as indicators of human cognitive processing.

Rotated-factor Solution

To achieve a simpler structure and a more meaningful pattern, the principal-factor solution was rotated according to the varimax procedure. The results of this rotation for the brain asymmetry and cognitive attributes data are listed in Table 12. Eight significant factors accounted for 74.4 percent of the variance. The terminal factors, in order of diminishing percentages of the variance accounted for, are described below.

1. Factor 1 was characterized by auditory and bimodal asymmetries in the frontal, temporal, and parietal areas (11.8% of the variance).

2. Factor 2 was characterized by visual and bimodal asymmetries in the temporal and parietal areas (11.2% of the variance).

3. Factor 3 was a cognitive dimension characterized by VERB, AFQT, LOG, REFL, SPA, and RGL (10.6% of the variance).

4. Factor 4 was characterized by visual and bimodal asymmetries in the occipital areas (8.8% of the variance).

5. Factor 5 was characterized primarily by TOL, CATW, AFQT, SPA, and LOG and secondarily by bimodal asymmetry in the parietal regions (8.3% of the variance).

6. Factor 6 was characterized by visual and bimodal asymmetries in the frontal areas and by RGL (8.2% of the variance).

7. Factor 7 was characterized primarily by auditory asymmetry in the occipital regions and FLD and secondarily by SPA and CATW (8.1% of the variance).

8. Factor 8 was a cognitive dimension characterized by CON, COG, SPA, RGL, and LOG (7.4% of the variance).

Factors 1, 2, and 4, defined primarily by brain asymmetry measures, jointly accounted for approximately 32 percent of the variance. Factors 3 and 8, characterized chiefly by psychometric measures of abilities, aptitudes, and cognitive styles, together accounted for about 18 percent of the variance. Factors 5, 6, and 7, specified by brain asymmetry and cognitive psychometric measures, accounted for approximately 24 percent of the variance. These statistics imply that a major portion of the variability in the data was attributed to brain asymmetry measures either acting independently (32%) or interactively with cognitive measures (24%). These later factors, 5, 6, and 7, suggest that some ERPs and cognitive characteristics contribute to or define the same underlying independent dimensions. That is, they weight the same factors, implying that they are related.

Table 12

Varimax-factor Matrix for the Brain Asymmetry Measures and Cognitive Characteristics Data

Measure	Factors 1	2	3	4	5	6	7	8
Visual Asymmetry								
Frontal	.00	.11	.10	.00	.15	.86	.09	.07
Temporal	.01	.81	-.15	.00	.17	.24	.01	-.03
Parietal	.07	.86	.05	.13	-.05	.00	.17	.14
Occipital	.02	.21	.03	.86	.06	-.08	.11	.03
Auditory Asymmetry								
Frontal	.82	-.12	.15	.20	.09	.05	-.13	.02
Temporal	.86	.27	-.12	-.01	.02	.05	.08	-.01
Parietal	.75	.37	-.07	-.21	-.10	.04	.30	-.18
Occipital	.12	.17	-.06	.14	.14	-.01	.77	-.14
Bimodal Asymmetry								
Frontal	.41	.04	-.16	.07	-.15	.67	-.17	.22
Temporal	.36	.70	-.01	.36	-.11	.06	-.03	-.01
Parietal	.48	.57	.12	.15	-.51	-.14	.03	.00
Occipital	.05	.08	.10	.91	-.05	.07	.04	.08
Cognitive Style								
FLD	-.09	.01	.30	.00	-.05	.17	.74	.22
CON	-.26	.08	.22	.08	.13	.04	.12	.74
REFL	.03	-.04	.52	-.26	-.16	.31	.19	-.06
TOL	.10	-.02	.05	.04	.67	-.09	.22	-.08
CATW	-.12	.05	.19	-.08	.61	.19	-.33	-.01
COG	.13	.04	-.25	.03	-.22	.09	-.08	.72
Aptitude and Ability								
AFQT	-.08	-.02	.64	.18	.50	-.10	.28	.18
RGL	.12	-.21	.38	.09	.17	-.58	-.22	.35
VERB	-.02	-.03	.85	.20	.06	-.15	.07	.07
SPA	.13	-.03	.39	.16	.44	-.25	.39	.40
LOG	.00	.02	.61	-.04	.35	.01	-.19	-.35
Associated Eigenvalue	2.71	2.59	2.43	2.03	1.91	1.89	1.86	1.70
% Variance Accounted for	11.78	11.24	10.58	8.81	8.32	8.21	8.10	7.37
Cumulated % Variance	11.78	23.02	33.60	42.41	50.73	58.94	67.04	74.41

Note. Only factors with associated eigenvalues greater than or equal to 1.0 are tabulated. This minimum eigenvalue criterion may ensure that only factors accounting for at least the amount of total variance of a single variable are significant.

DISCUSSION AND CONCLUSIONS

Highlighting only a few of the significant results of the product-moment analyses, canonical correlational analyses, and the varimax rotated-factor solution, it appears that complex information processing may be related to brain activity evoked bimodally in the left and right frontal and parietal regions. This is evident from some of the results of the product-moment and canonical correlations as well as the varimax factor rotation. Some of the product-moment correlations showed that complicated cognitive attributes such as AFQT and RGL are related to bimodal ERPs in the left parietal and both frontal areas. The variances that AFQT had in common with bimodal ERPs in the left frontal, left parietal, and right frontal regions, for example, were 34, 86, and 21 percent respectively. RGL had 59, 61, and 40 percent shared variance with bimodal ERPs produced at these respective sites. These variances were derived from data presented in Table 6.

Several canonical correlations also revealed that AFQT and RGL were associated with bimodal ERPs in the left and right frontal and parietal sites. For example, in the largest canonical correlation found (R_c = .97), AFQT and RGL were correlated with bimodal ERPs in the left frontal and parietal areas. These cognitive attributes and ERPs had 95 percent variance in common. The second largest canonical correlation (R_c = .96) was between AFQT and bimodal ERPs in the left parietal region; these shared 92 percent of the variance. Another example of a strong canonical correlation (R_c = .75) was that between AFQT and bimodal asymmetry in the parietal sites; these had 58 percent variance in common.

Even some of the findings of the varimax rotated-factor solution suggest that AFQT and RGL are associated with bimodal ERPs in the parietal and frontal areas. Specifically, Factor 5 (8.3% of the variance) implies that AFQT is related to bimodal asymmetry in the parietal regions; and Factor 6 (8.2% of the variance), that RGL is related to bimodal asymmetry in the frontal areas.

These spotlighted results of the product-moment, canonical, and factor analyses seem to indicate that complex information processing as indexed by AFQT and RGL is associated with brain activity in the frontal and parietal regions. The AFQT is composed of three subtests covering word knowledge, arithmetic reasoning, and space perception. Each of these component tests in turn represents a particular type of complicated processing (i.e., comprehending language, solving arithmetic problems, and visualizing objects in space). RGL also consists of separate, though highly related, components having to do with understanding English words and prose passages. Conducting analyses of the cognitive constituents of AFQT and READ would certainly further reveal the nature and complexity of the information processing involved in these subtasks. For example, Frederiksen (1980) and Hunt (1980) have conducted and discussed componential analyses of reading skill and verbal comprehension respectively. They have demonstrated that these behaviors consist of many complicated information-processing components as attending, encoding, storing, retrieving, and decoding.

The performances required by the AFQT and RGL measures and the results of the correlational and factor analyses disclose that brain activity elicited bimodally in the left and right frontal and parietal areas may be related to complex information processing. The strong associations established between AFQT, RGL, and these bimodal ERPs should not, however, overshadow the importance of the many other significant relationships uncovered by this study.

The construct validity of ERPs as indicators of individual differences in human cognitive processing or styles is demonstrated by the relationships given in the following examples:

1. FLD and CON are associated with visually elicited ERPs in the occipital areas, sharing as much as 16 percent variance.

2. VERB is associated with auditory ERPs in the frontal areas, sharing approximately 12 percent of the variance.

3. TOL and COG are related to sensory interaction in the frontal, temporal, parietal, and occipital sites, having about 15 percent variance in common.

With respect to cognitive styles, the product-moment correlations revealed that visual ERPs in the parietal and occipital regions were negatively related to cognitive complexity; and bimodal ERPs in the left parietal and occipital regions, positively related to tolerance of ambiguity. Individuals who are high in cognitive complexity seem to process information at both rear parts of the brain, as indicated by decreases in amplitudes at the parietal and occipital areas. Also, those who are high (low) in tolerance of ambiguity appear to have high (low) amplitudes at the left parietal and occipital sites as demonstrated by bimodal ERPs. Generally, some ERP asymmetries do not seem to be strongly related to the traditional measures of cognitive styles that were used in this study.

Sensory interaction indices, however, were found to be positively related to cognitive complexity. Possibly, facilitation at left and right hemisphere sites is related to perceiving the environment in a multidimensional manner as assessed by COG. Also, it was established that TOL appears to be positively associated with activity in the left back of the brain, the parietal and occipital areas, and in the right front of the brain, the frontal and temporal areas. Being able to tolerate ambiguous situations and ideas has been customarily associated with intelligence, which has in turn been related to the left parietal region (Lewis, Rimland, & Callaway, 1977).

Considering aptitudes and abilities, the product-moment correlations suggested many interesting relationships. Spotlighting only some of these, visual ERPs revealed that both frontal, temporal, and parietal regions were positively related to AFQT and RGL. A few of these findings somewhat substantiated Lewis and Rimland's (1976) results that right frontal and left parietal amplitudes elicited by visual stimuli were associated with predicting success in a Navy remedial reading program. Lewis, Rimland, and Callaway (1977) also suggested that left parietal amplitudes triggered by visual stimuli are related to AFQT. This previous finding is compatible with some of the results reported in this study. Lewis and Froning (1981) demonstrated that the left parietal and right temporal areas discriminated between high and low reading groups using visual ERPs. Their investigation, together with the present study, indicated the importance of these sites for reading skill.

This research, unlike the Lewis and Froning findings regarding auditory ERPs, suggested the importance of the left frontal, temporal, and parietal regions for AFQT and RGL. With respect to bimodal ERPs, it appeared that not only the four left hemisphere sites but also the two forward parts of the right hemisphere, frontal and temporal areas, are positively associated with AFQT and RGL. Correlations between bimodal ERP asymmetries and aptitudes and abilities suggested that the back parts of the brain, parietal and occipital regions, unlike the front parts, frontal and temporal areas, are associated with AFQT and RGL. This is similar to Lewis, Rimland, and Callaway's (1977)

finding that asymmetry at the parietal areas significantly distinguished between high and low AFQT groups.

AFQT and RGL were also found to be positively correlated with sensory interaction indices in the left parietal and occipital regions. These results are somewhat similar to Lewis and Froning's (1981) findings that sensory interaction indices for left and right occipital and right temporal areas separated high and low reading groups. It is interesting to note that, in this present study, there were almost no significant correlations between right hemisphere sensory interaction indices and AFQT. Left hemisphere sensory interaction does seem to be related to higher order cognitive functions as assessed by AFQT and RGL. Possibly, there is more attenuation in the left than the right hemisphere, which would account for the importance of the former over the latter with respect to AFQT and RGL. This notion is somewhat supported by Lewis, Federico, Froning, and Calder's (1981) finding that a verbal group, when compared with a spatial group, exhibited greater inhibition in the left hemisphere than in the right due to bimodal stimuli presentation. It is feasible to assume that more activation was occurring in the left hemisphere, the one that is considered to be most involved in verbal processing.

Many of the findings from this present research corroborated to some extent the results of a number of other studies: Right hemisphere ERP amplitudes and asymmetry measures appear to be directly related to intelligence--but not always (Bigum, Dustman, & Beck, 1970; Galbraith, Gliddon, & Busk, 1970; Perry, McCoy, Cunningham, Falgot, & Street, 1976; Rhodes, Dustman, & Beck, 1969; Richlin, Weisinger, & Weinstein, Giannini, & Morganstern, 1971; Shucard & Horn, 1973).

This study's more salient findings, as indicated, were that many ERPs, especially those elicited in the frontal and parietal regions, were strongly related to general aptitude and reading comprehension as indexed by AFQT and RGL respectively. According to Snow (1980), Cattell's (1971) crystallized ability, G_c, represents a general dimension of measures that are good predictors of conventional educational achievement or scholastic ability (e.g., verbal, quantitative, vocabulary, reading comprehension, information, mathematical, and prior scholastic achievement). Cattell's (1971) fluid ability, G_f, represents another general dimension of measures that probably represents assembly and control processes necessary to structure adaptive strategies for solving novel and immediate problems (e.g., abstract, spatial, figural, and nonverbal reasoning tests).

In attempting to answer why G_c measures are often better predictors of learning than G_f measures, Snow (1980, p. 37) speculated:

> One reason may be that G_c represents the long-term accumulation of knowledge and skills, organized into functional cognitive systems by prior learning, that are in some sense crystallized as units for use in future learning. Because these are products of past education, and because education is in large part accumulative, transfer relations between past and future learning are assured. The transfer need not be of specific knowledge but rather of organized academic learning skills. Thus G_c may represent prior assemblies of performance processes retrieved as a system and applied new in instructional situations not unlike those experienced in the past, whereas G_f may represent new assemblies of performance processes needed in more extreme adaptations to novel situations. The distinction, then, is better long-term assembly for transfer to familiar new situations versus short-term assembly for transfer to unfamiliar new situations.

This distinction between G_c and G_f suggests that bimodal ERPs in the frontal and parietal regions of the brain are primarily indicators of crystallized intelligence. In this study, bimodal ERPs from these areas were found to be very strongly associated with general aptitude (i.e., comprehending language, solving arithmetic problems) and reading skill (i.e., understanding English words and prose passages) that are chiefly measures of crystallized intelligence.

Neuroanatomical substrates have been identified that contribute some support to this theory. Brodmann's segments 9, 10, 11, and 12 in the frontal lobe of the brain constitute "association" areas. These regions apparently project as well as receive a number of long, primary, association bundles that interconnect the different parts of each hemisphere (Goldman-Rakic & Schwartz, 1982; Grossman, 1967; Peele, 1961). Consequently, it is possible that these areas can readily interact or associate with practically all other segments of the cortex. These numerous interconnections could serve as the neuroanatomical analogue for crystallized intelligence: long-term storage of knowledge and skills, structured into functional cognitive systems by previous experience, established assemblies of performance processes retrieved as a system and used in new instructional situations similar to those of the past.

If some ERPs are indeed correlates of crystallized intelligence, as suggested, then Navy managers who are responsible for developing and evaluating procedures for selecting and classifying incoming personnel, as well as assigning and adapting specific curricula to them, have another possible option. Results obtained from paper-and-pencil tests of ability, aptitude, and achievement are, by their very nature, confounded or intermingled with reading skills of the personnel being assessed. It now becomes feasible to obtain more accurate measures, which are devoid of this confounding, of individuals' crystallized intelligence by using ERP technology. This would be true especially for those personnel who have a low reading ability that prohibits them from doing as well on paper-and-pencil tests as they might without this handicap.

Some of what must be considered in the decision to employ paper-and-pencil tests versus ERP procedures to evaluate crystallized intelligence are the incurred costs, expended energy, spent time involved in each of these two alternative assessment techniques. When this is done, employing ERP technology to estimate the crystallized intelligence of some individual incoming or on-board personnel seems reasonable and viable at this time in light of cost, labor, and time restraints.

The findings of the research presented in this report:

1. Suggest that ERP procedures can be used to study the relationships between electrical activity in the brain and human cognition.

2. Confirm the possibility of employing brain ERPs for indexing certain cognitive styles, abilities, and aptitudes.

3. Imply that ERPs reflect individual differences in intellectual function.

4. Establish ERP correlates of crystallized intelligence.

5. Demonstrate the construct validity of brain ERPs as indicators of human cognitive processing.

Several limitations of this research should be noted. The ERP recordings were not obtained at the same time the subjects were taking the written tests. This research

should be replicated using a larger subject sample. The assumption was made that cognitive style, ability, and aptitude tests having moderate to high reliability, such as those used in this research, do in fact measure individual differences in information processing.

DIRECTION OF RESEARCH

Since ERPs appear to be valid measures of individual differences in human information processing, especially in crystallized intelligence, they may provide a basis for developing adaptive instructional techniques. Research is now underway that records ERPs prior to and during the initial learning and subsequent performance of Navy-relevant, real-world, information-processing tasks (e.g., detecting, analyzing, recognizing, and classifying radar signals). While the research subjects are learning and performing these tasks, ERP measures are obtained, along with error patterns, hit-and-miss rates, and student achievement. These learning and performance indices are being related to the ERP measures to determine their possible use for designing adaptive instructional strategies and for predicting student performance.

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